ELSEVIER

Earth and Planetary Science Letters 123 (1994) 139–154

EPSL

East Mariana Basin tholeiites: Cretaceous intraplate basalts or rift basalts related to the Ontong Java plume?

P.R. Castillo [a], M.S. Pringle [b], R.W. Carlson [c]

[a] *Scripps Institution of Oceanography, La Jolla, California 92093-0220, USA,*
[b] *United States Geological Survey, Menlo Park, California 94025, USA,*
[c] *Carnegie Institution of Washington, 5241 Broad Branch Road, N.W., Washington, D.C. 20015, USA*

(Received October 10, 1993; revision accepted February 4, 1994)

Abstract

Studies of seafloor magnetic anomaly patterns suggest the presence of Jurassic oceanic crust in a large area in the western Pacific that includes the East Mariana, Nauru and Pigafetta Basins. Sampling of the igneous crust in this area by the Deep Sea Drilling Program (DSDP) and the Ocean Drilling Program (ODP) allows direct evaluation of the age and petrogenesis of this crust. ODP Leg 129 drilled a 51 m sequence of basalt pillows and massive flows in the central East Mariana Basin. $^{40}Ar/^{39}Ar$ ages determined in this study for two Leg 129 basalts average 114.6 ± 3.2 Ma. This age is in agreement with the Albian–late Aptian paleontologic age of the overlying sediments, but is distinctively younger than the Jurassic age predicted by magnetic anomaly patterns in the basin.

Compositionally, the East Mariana Basin basalts are uniformly low-K tholeiites that are depleted in highly incompatible elements compared to moderately incompatible ones, which is typical of mid-ocean ridge basalts (MORB) erupted near hotspots. The Sr, Nd and Pb isotopic compositions of the tholeiites ($^{87}Sr/^{86}Sr_{init} = 0.70360$–$0.70374$; $^{143}Nd/^{144}Nd_{init} = 0.512769$–$0.512790$; $^{206}Pb/^{204}Pb_{meas} = 18.355$–$18.386$) also overlap with some Indian Ocean Ridge MORB, although they are distinct from the isotopic compositions of Jurassic basalts drilled in the Pigafetta Basin, the oldest Pacific MORB. The isotopic compositions of the East Mariana Basin tholeiites are also similar to those of intraplate basalts, and in particular, to the isotopic signature of basalts from the nearby Ontong Java and Manihiki Plateaus. The East Mariana Basin tholeiites also share many petrologic and isotopic characteristics with the oceanic basement drilled in the Nauru Basin at DSDP Site 462. In addition, the new 110.8 ± 1.0 Ma $^{40}Ar/^{39}Ar$ age for two flows from the bottom of Site 462 in the Nauru Basin is indistinguishable from the age of the East Mariana Basin flows. Thus, while magnetic anomaly patterns predict that the igneous basement in the Nauru and East Mariana Basins is Jurassic in age, the geochemical and chronological results discussed here suggest that the basement formed during a Cretaceous rifting event within the Jurassic crust. This magmatic and tectonic event was created by the widespread volcanism responsible for the genesis of the large oceanic plateaus of the western Pacific.

1. Introduction

The East Mariana Basin strikes roughly west–southeast in the western Pacific. It is bounded to the east by the Marshall-Gilbert Island Chain, to the north by the Magellan Seamounts, to the west and northwest by the Mariana Trench, and to the south by the Caroline Ridge (Fig. 1). During ODP Leg 129, the central part of the East Mariana Basin at 12°5.8′N and 153°12.6′W (ODP Site

---

[CL]

SSDI 0012-821X(94)00036-X

802) was drilled in search of a Jurassic sedimentary sequence and its underlying igneous basement [1]. This was carried out immediately following the first ever successful penetration of Jurassic crust in the Pigafetta Basin during the same cruise. The predicted age of the seafloor in the East Mariana Basin is Jurassic, based on a simple extrapolation of the seafloor magnetic lineation pattern to the north of the basin. The magnetic anomaly age is consistent with the low amplitude magnetic lineation pattern of the seafloor in the two basins; interpreted as being due to their accretion during the long Jurassic 'magnetic quiet event', 145–170 Ma [2].

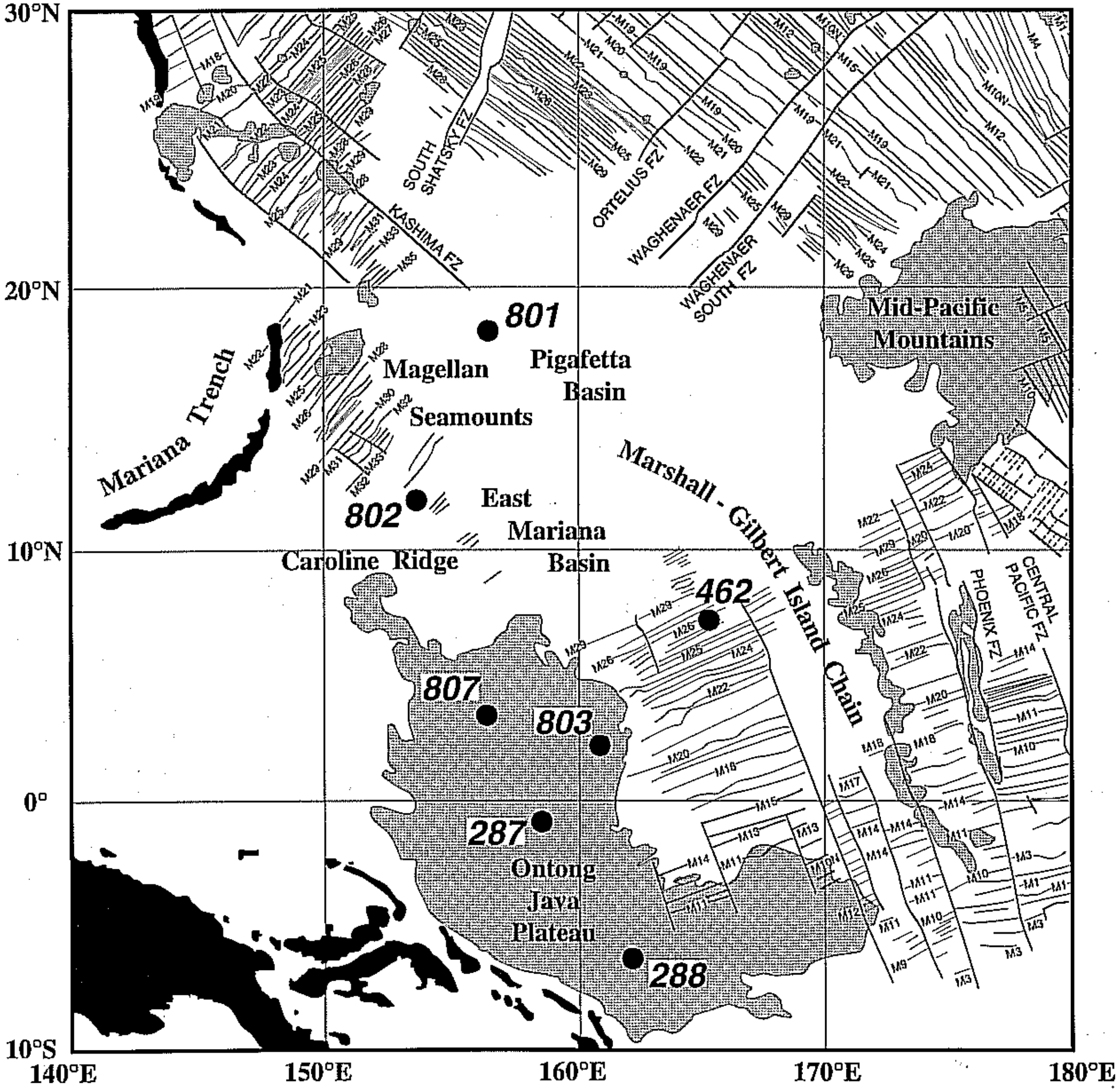

Fig. 1. Map of the western Pacific showing Mesozoic magnetic anomaly lineations [after Nakanishi et al., 32,33] and locations of the East Mariana Basin, Nauru Basin, East Pigafetta Basin and Ontong Java Plateau. Dots with numbers represent DSDP and ODP sites mentioned in the text.

The main objective of this paper is to present the age, petrology and most probable origin of the East Mariana Basin igneous basement. To attain this objective, the geochemistry and petrogenesis of the tholeiites were investigated and compared to those of the tholeiites recovered from DSDP and ODP drill sites on the Ontong Java Plateau, Nauru Basin and Pigafetta Basin (Fig. 1). Special emphasis is placed on the incompatible trace elements, particularly the rare earth elements (REE), and Sr, Nd and Pb isotope ratios, because these are most clearly diagnostic of their mantle source [3]. The temporal evolution of all the tholeiites were also compared to each other using recently available radiometric age data for all samples. In addition, new $^{40}Ar/^{39}Ar$ total fusion ages for two tholeiites from the bottom of DSDP Site 462 in the Nauru Basin were determined in this study.

2. Samples and methodology

ODP Leg 129 drilled through ~ 509 m of sedimentary rocks and ~ 51 m of basaltic lavas at Site 802. Based on biostratigraphy, the age of the lowermost sedimentary rocks is Albian–late Aptian: no Jurassic sediments were found [1]. Two samples of the lava flows directly beneath the sediments give a $^{40}Ar/^{39}Ar$ total fusion age of 114.6 ± 3.2 Ma [4], compatible with the biostratigraphic age of the sediments. The lavas drilled in the East Mariana Basin consist of pillows and massive flows that have aphanitic to glassy margins and hypocrystalline interiors, consisting chiefly of plagioclase, augite, glass, olivine (almost always pseudomorphed by clays) and lesser amounts of titanomagnetite. East Mariana Basin lavas are tholeiites, with a limited range of major element compositions (e.g., $SiO_2 = 49–51$ wt%, $MgO = 6.7–8.1$ wt% and $CaO = 11–12$ wt%). They have low K_2O (0.03–0.26 wt%), TiO_2 (0.99–1.24 wt%) and P_2O_5 (0.02–0.10 wt%) contents and are depleted in incompatible trace elements with respect to mildly incompatible ones (e.g., $Zr/Hf = 35–43$; $Ta/La = 10–16$; $La/Sm_n = 0.82–0.90$). These bulk-rock compositions are typical of mid-ocean ridge basalts (MORB) [5].

The alteration aspects of East Mariana Basin tholeiites have also been discussed by Alt et al. [6] and Busch et al. [7]. These tholeiites are fresh to only slightly altered (< 2–10% alteration) and have physical and chemical properties that are indistinguishable from young (< 10 Ma), typical MORB crust.

Additional fresh glasses taken from the margins of pillow lavas were analyzed for this study. Major element contents of these glasses were kindly determined by T. O'Hearn using the electron microprobe at the Smithsonian Institution and the procedure described by Melson et al. [8]. Accuracy and precision are generally better than 3% for each oxide. Rare earth element (REE) and Co, Cs, Hf, Sc, Ta and Th contents of aliquots of these glasses were determined at Washington University by instrumental neutron activation analysis (INAA) using the procedure described by Jacobs et al. [9], with some modifications. Accuracy and precision for the trace element contents reported are generally better than 2%. All trace element data for the Nauru Basin and Pigafetta Basin tholeiites used in the comparative study, apart from for those from the Ontong Java Plateau, were also produced at Washington University. For Ontong Java Plateau tholeiites, only those trace element data analyzed by INAA [10] were used in the comparison.

The Sr, Nd and Pb isotopic compositions of the East Mariana Basin tholeiite glasses were analyzed at the Carnegie Institution of Washington using the procedure described by Castillo et al. [11,12]. The Pb isotopic composition of a holocrystalline sample (802A-62-3, 12-18) was also analyzed to compare the Pb isotopic compositions of fresh glass and slightly altered hypocrystalline interior. Additionally, the Pb isotopic compositions of Nauru Basin tholeiite glasses (462A-51-4, 28-30 and 462A-56-1, 9-10), previously analyzed for their Sr and Nd isotopic compositions [13], and kindly provided by J. Mahoney, were also measured to investigate any difference in the Pb isotopic compositions between Nauru Basin whole-rocks and glasses. All the isotopic composition measurements of the Nauru and Pigafetta Basin samples used in the comparative study were made at the Carnegie Institution.

Table 1
Major and trace element and Sr, Nd, and Pb isotopic compositions of East Mariana Basin and Nauru Basin tholeiite glass and representative whole rock samples

Hole	802A	802A	802A	802A	802A	802A	802A	802A	802A	462A	462A
Core-Sect.	58-2	58-2	58-3	58-4	59-3	59-2	59-1	62-1	62-3	51-4	56-1
Top–bottom (cm)	110–115	142–149	0–1	65–70	130–136	123–127	127–132	112–118	12–18	28–30	9–10
Depth (mbsf)	518.66	518.92	519	521.15	526.7	528.13	529.6	551.7	553.6	783.3	806.6
Type of sample	G	G	G	G	W–R	G	W–R	W–R	W–R	G*	G*
SiO_2	51.40	52.09	–	51.58	50.56	51.69	51.32	51.36	51.4	50.55	51.01
TiO_2	1.16	1.16	–	1.16	1.12	1.15	1.22	1.07	1.10	1.02	0.98
Al_2O_3	13.97	13.86	–	14.05	14.4	14.08	14.52	14.27	14.56	14.38	14.07
FeO_{total}	12.55	12.18	–	12.40	11.90	12.36	10.94	11.47	1.24	11.61	11.25
MgO	6.90	6.77	–	6.91	7.78	6.79	7.87	7.88	7.76	8.07	7.81
CaO	11.79	11.75	–	11.74	12.04	11.71	12.01	11.86	11.86	12.11	12.79
Na_2O	1.99	1.96	–	1.95	1.95	2.00	2.01	1.98	1.96	2.13	2.08
K_2O	0.12	0.12	–	0.11	0.14	0.10	0.08	0.08	0.07	0.12	0.01
P_2O_5	0.13	0.10	–	0.10	0.02	0.13	0.02	0.02	0.02	–	–
Total	100.0	100.0	–	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Co	44	48	47	48	50	48	50	49	49	51	49
Cs	0.3	–	–	0.3	0.1	0.2	0.2	0.3	0.2	–	–
Hf	1.66	1.83	1.79	1.83	1.65	1.69	1.76	1.63	1.73	1.50	1.50
Sc	48	49	49	49	48	49	49	48	48	46	46
Ta	0.15	0.18	0.18	0.17	0.18	0.19	0.17	0.17	0.18	–	–
Th	0.19	0.18	0.17	0.23	0.22	0.20	0.20	0.19	0.23	–	–
La	3.01	3.16	3.09	3.18	3.16	3.14	3.13	3.02	3.13	2.54	2.53
Ce	7.7	8.2	7.9	8.3	8.1	8.7	8.3	8.1	7.9	7.2	6.8
Sm	2.19	2.32	2.31	–	2.35	2.31	2.25	2.21	2.34	1.93	2.24
Eu	0.81	0.85	0.86	–	0.86	0.88	0.86	0.85	0.83	0.79	0.79
Tb	0.53	0.56	0.57	0.57	0.57	0.56	0.60	0.55	0.54	0.51	0.51
Yb	2.32	2.35	2.41	2.41	2.37	2.43	2.36	2.30	2.34	2.09	2.12
Lu	0.35	0.36	0.36	0.36	0.36	0.36	0.37	0.36	0.37	0.31	0.34
$^{87}Sr/^{86}Sr_{init}$	0.70372	0.70365	0.70365	0.70360	–	0.70361	–	–	0.70374	0.70359	0.70360
$^{143}Nd/^{144}Nd_{init}$	0.512804	0.512801	0.512790	0.512769	–	0.512789	–	–	–	0.512817	0.512828
$^{206}Pb/^{204}Pb_{meas}$	18.367	18.380	18.386	18.367	–	18.380	–	–	18.355	18.545	18.355
$^{207}Pb/^{204}Pb_{meas}$	15.507	15.511	15.510	15.500	–	15.491	–	–	15.493	15.516	15.526
$^{208}Pb/^{204}Pb_{meas}$	38.369	38.390	38.380	38.346	–	38.336	–	–	38.296	38.413	38.296

– = not analyzed; G = glass; W–R = whole rock. G* = Nauru Basin glass previously analyzed by J. Mahoney [13] for their $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ compositions; the major and trace element compositions of these samples are for their whole-rock interiors previously reported in [20].

Two samples from the lowermost flows recovered ~1200 m bsf at DSDP Site 462 in the Nauru Basin (462A-106-2, 54-61 and 462A-108-2, 4-9) were dated by the $^{40}Ar/^{39}Ar$ incremental heating technique. The analyses were carried out at the US Geological Survey age dating laboratory at Menlo Park, California, following the procedures described by Pringle [4,14]. Both samples are medium-grained (1–5 mm), holocrystalline interiors of lava flows and are only slightly to moderately (2–10%) altered.

3. Results

The tholeiite glasses analyzed have almost identical bulk compositions (Table 1). As expected [e.g., 3], there are subtle but systematic differences between bulk-rock analyses and glass analyses. Total Fe as FeO* and P_2O_5 are lower in the hypocrystalline interior than in the glass, whereas the reverse is true for MgO. Although it is possible that the discrepancy is due to analytical bias between electron microprobe and XRF

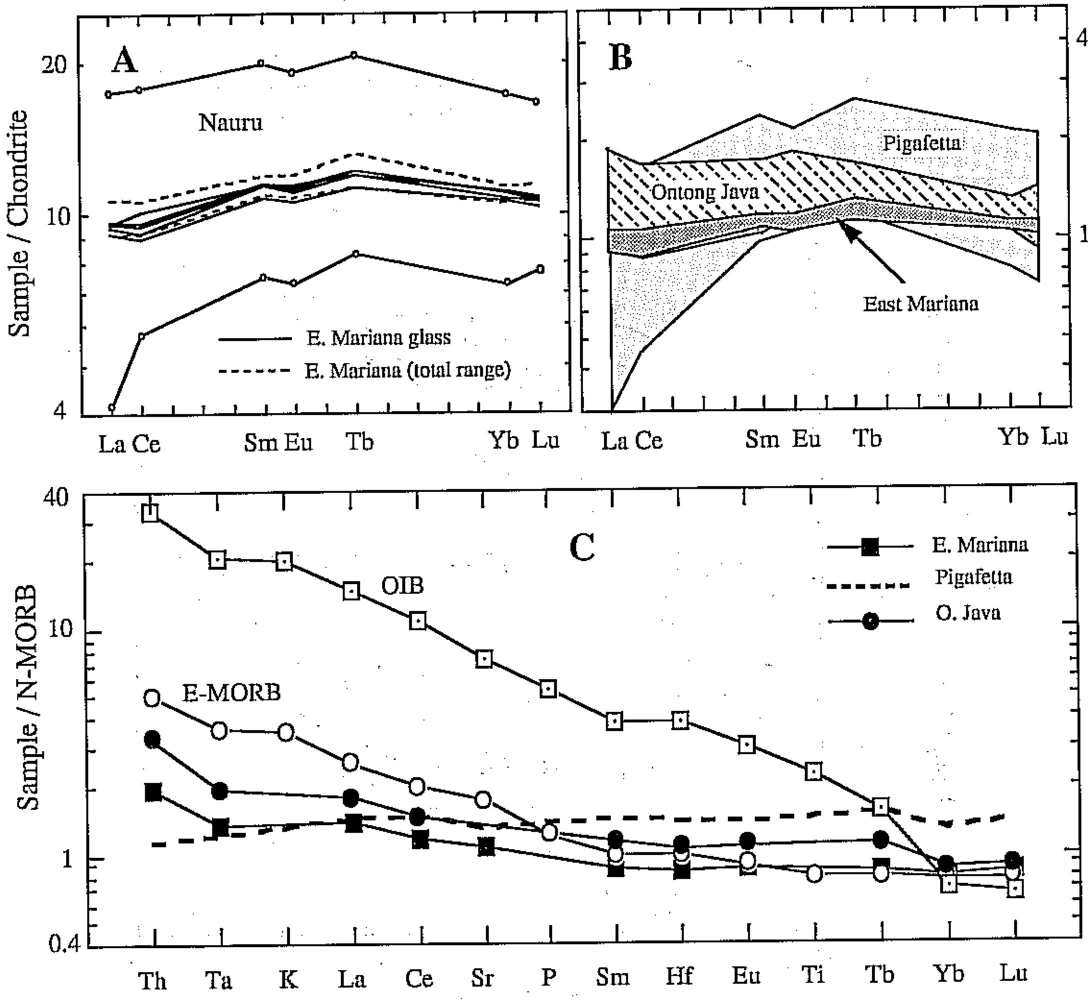

Fig. 2. Chondrite-normalized REE concentration patterns of tholeiitic basalts. (A) From the East Mariana Basin and Nauru Basin and (B) from the East Mariana Basin, Pigafetta Basin and Ontong Java Plateau. (C) N-MORB normalized average trace element concentration patterns of tholeiitic basalts from the East Mariana Basin, Pigafetta Basin and Ontong Java Plateau. Concentration patterns of average E-MORB and OIB are shown for reference.

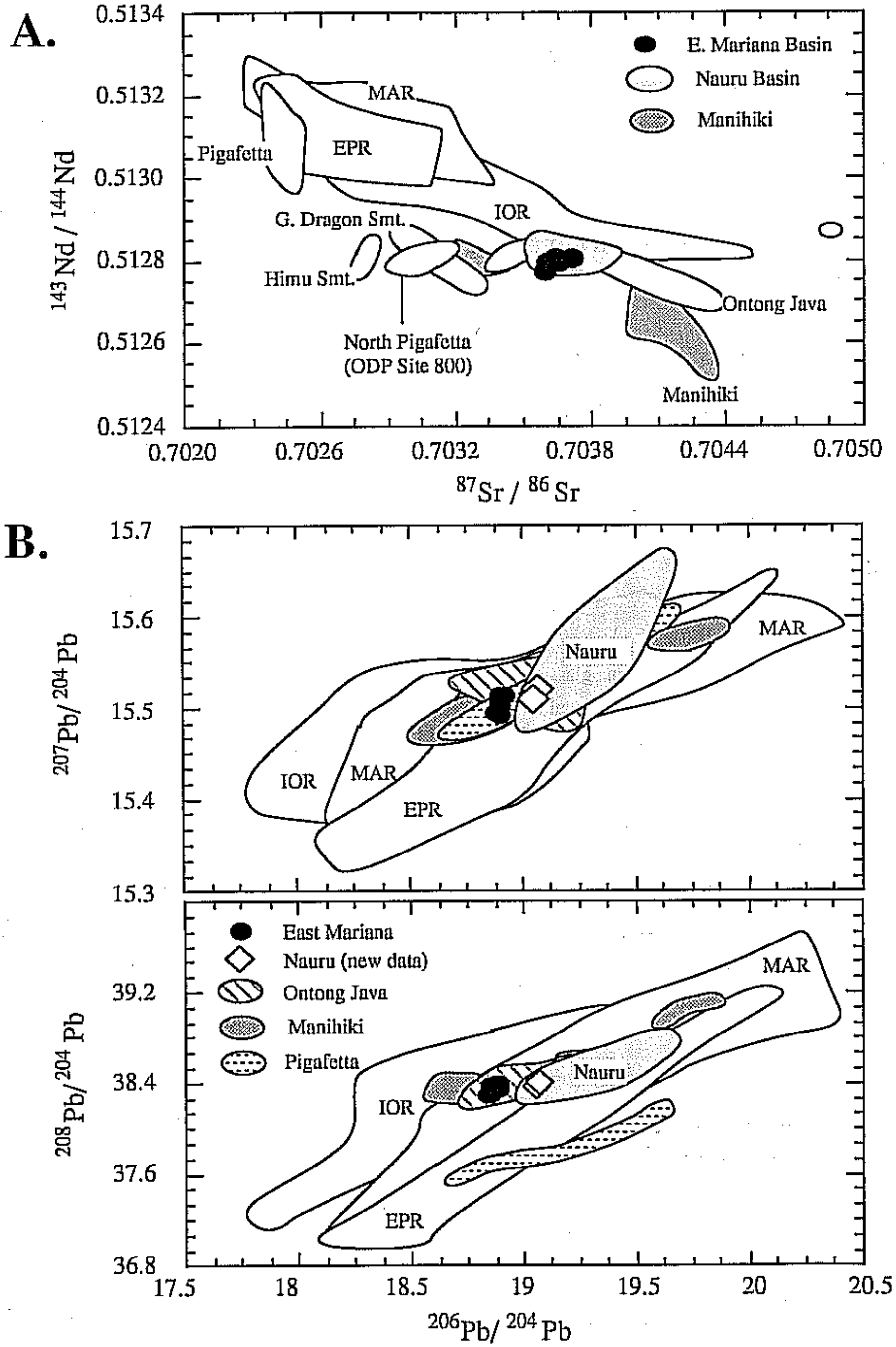

Fig. 3. (A) $^{87}Sr/^{86}Sr$ against $^{143}Nd/^{144}Nd$ and (B) $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ against $^{206}Pb/^{204}Pb$ plots for the East Mariana Basin tholeiites. Analytical errors are smaller than the symbols used. Fields for tholeiitic basalts from the Pigafetta Basin, Nauru Basin, Ontong Java Plateau, Manihiki Plateau and other selected oceanic basalts are shown for reference.

analyses, we believe that this is due to selective accumulation of phenocrysts, most likely olivine, in the hypocrystalline portion of the lavas. A similar discrepancy in major element compositions of coexisting glass–whole rock pairs due to phenocryst redistribution has been documented by Staudigel and Bryan [15].

The apparent difference in the major element compositions of the whole-rock interior and glass margin, however, completely disappears in the trace element analyses (Table 1). East Mariana Basin tholeiite glasses have very similar trace element compositions, which overlap completely with those of the whole-rock data. All samples have a REE content of about nine to thirteen times chondrite abundances and a slightly convex-upward chondrite-normalized REE pattern, with a small, but distinctive, negative Eu anomaly (Figs. 2a and b). Their highly incompatible trace element abundances are intermediate between normal-(N-)MORB and enriched-(E-)MORB, and definitely lower than ocean island basalts (OIB; Fig. 2c). Moreover, the ratios of highly incompatible to moderately incompatible elements in the East Mariana Basin tholeiites, such as Ta/La, La/Sm and La/Yb, are only slightly higher than N-MORB but are much lower than those of OIB.

Table 2
Ages of the tholeiites drilled by the DSDP and ODP in the western Pacific

Sample	Type	^{40}Ar/^{39}Ar age	Best age estimate	Source of data	Fossil age of the nearest sediment	Source of data
East Mariana Basin tholeiites						
802A, 62-2, 45-50	whole rock	116.8 ± 4.8	114.6 ± 3.2	[4,14]	early Aptian–Albian	[1]
(duplicate)		112.5 ± 4.6				
802A, 62-3, 4-12	whole rock	116.0 ± 13.1				
Nauru Basin tholeiites						
462A, 32-1, 46-49	whole rock	110 ± 3	–	[19]	Cenomanian	[20]
462A, 106-2, 54-61	whole rock	111.6 ± 1.5	110.8 ± 1.0	this study	late Jurassic–early Aptian	[17]
(duplicate)		109.9 ± 1.4				
462A, 108-2, 4-9	whole rock	113.6 ± 4.5				
(duplicate)		100.5 ± 24.1				
Ontong Java Plateau tholeiites						
807C, 75-2, 129-131	whole rock	121.7 ± 3.6	122.3 ± 1.0	[10]	Aptian	[28,49]
807C, 78-1, 67-69	whole rock	124.0 ± 2.5				
807C, 80-1, 52-55	whole rock	122.4 ± 4.0				
807C, 84-6, 0-3	whole rock	122.6 ± 1.7				
807C, 90-1, 38-41	whole rock	119.5 ± 9.9				
807C, 93-3, 15-18	whole rock	126.0 ± 4.8				
289, 132-4, 79-81	whole rock	121.7 ± 2.7				
289, 132-4, 122-125	whole rock	122.7 ± 2.2				
Malaita 43	whole rock	118.9 ± 2.4	–	[10]	–	–
Malaita 8374	whole rock	114.7 ± 4.9				
803D, 71-2, 87-88	whole rock	85.7 ± 1.3	–	[10]	middle Cenomanian	[28]
803D, 69-1, 87-89	plagioclase	81.9 ± 2.5				
803D, 71-1, 14-16	plagioclase	81.5 ± 1.5				
(duplicate)		92.5 ± 2.8				
Pigafetta Basin tholeiites						
801C, 10-5, 53-58	whole rock	153.7 ± 8.0	166.8 ± 4.5	[4,14]	Callovian–Bathonian	[1]
801C, 10-6, 21-26	whole rock	173.0 ± 5.5				

Sources of data are listed in the References.

East Mariana Basin tholeiite glasses show a very small range in Sr, Nd and Pb isotopic compositions (Table 1). The Pb isotope data for the unleached whole rock (802A-62-3, 12-18) are fairly similar to the those for the glasses, despite its slightly higher $^{87}Sr/^{86}Sr$ ratio due to seawater alteration. Similarly, the Pb isotope data for the two Nauru Basin tholeiite glasses analyzed here (462A-51-4, 28-30 and 462A-56-1, 9-10) are within the range of those of the whole-rock data [11]. The East Mariana Basin tholeiites have slightly higher $^{87}Sr/^{86}Sr$ ratios for a given $^{143}Nd/^{144}Nd$ ratio than MORB from the East Pacific Rise (EPR) and the Mid-Atlantic Ridge (MAR; Fig. 3a). These tholeiites also have anomalously high $^{208}Pb/^{204}Pb$ for a given $^{206}Pb/^{204}Pb$, so that they plot distinctly above the field of MORB from the EPR (Fig. 3b). However, it is important to note that the Pb, Sr and, to a lesser extent, Nd isotope data for East Mariana Basin tholeiites plot within the fields for MORB from the Indian Ocean Ridges (IOR).

Radiometric age determinations were carried out because of the uncertainty in the age of the lava flows at the bottom of Hole 462A. Previous attempts to date these lavas [16] cannot be considered reliable because even the best of the experiments (462A-109-1, 106-108) did not pass the criteria for reliable $^{40}Ar/^{39}Ar$ ages as described by Pringle [4,14]. Although Late Jurassic to early Aptian age radiolarians were found in the sediments between lava flows at ~75 m above the bottom of Hole 462A, both Schaaf [17] and Primoli–Silva [18] noticed that some sections of the sedimentary sequence above the igneous complex may have been reworked. Thus, the interlava flow radiolarians may also be reworked and can provide only maximum age constraints on the bottom flows.

The age of the sills at the top of the Nauru Basin igneous complex is better constrained than that of the bottom flows. Ozima et al. [19] determined a 110 ± 3 Ma $^{40}Ar/^{39}Ar$ age for a basalt sill higher up in the igneous complex and this is

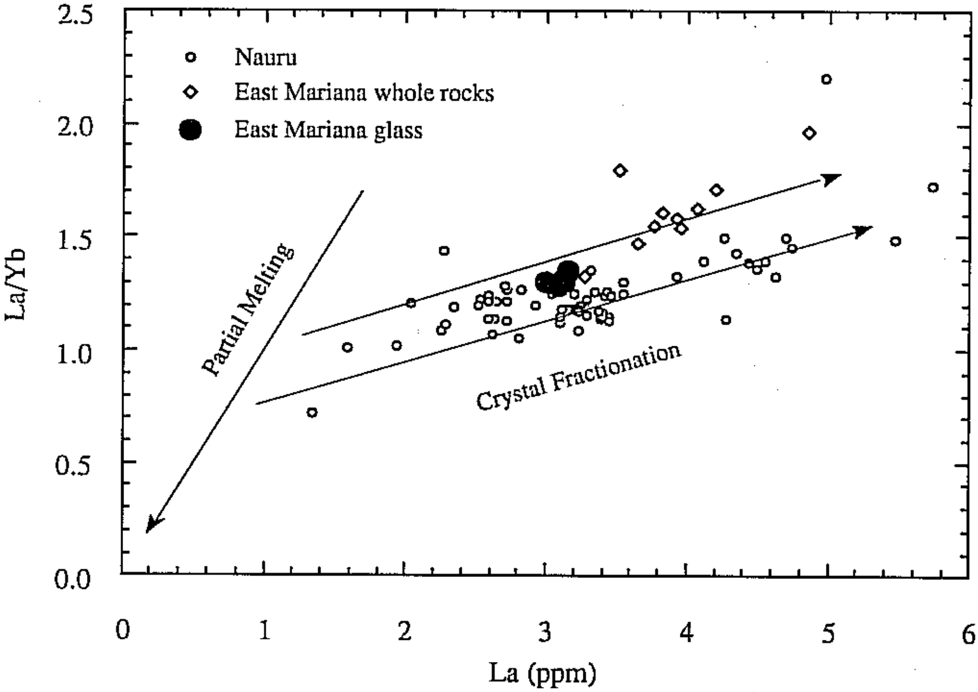

Fig. 4. La/Yb against La plot for the East Mariana Basin tholeiites. Nauru Basin tholeiites are also plotted for comparison. The two crystal fractionation paths represent the minimum number of crystallization paths to explain the range of the Nauru Basin tholeiite composition [11,27]. The East Mariana Basin tholeiites belong to one of these paths.

consistent with Albian or Cenomanian age of the sediments intruded by the sills [20]. Moreover, Hart and Staudigel [21] determined a minimum age of 105.1 ± 2.8 Ma for the vein mineral deposition in the Nauru Basin igneous complex.

The new weighted mean of the $^{40}Ar/^{39}Ar$ incremental heating ages of the Nauru Basin tholeiites is 110.8 ± 1.0 Ma (Table 2; see Pringle [14] for complete results). This age is identical with the previous $^{40}Ar/^{39}Ar$ age of the sills above the flows [19] and is younger than the Late Jurassic to early Aptian interlava flow sediments [17], which would indicate that these sediments are indeed reworked. This new age is also consistent with the normal polarity of the whole Nauru Basin igneous complex, suggesting that the whole complex must have been erupted after the M0 magnetic polarity event ~ 125 Ma [20,22]. If the ~ 111 Ma age is correct, then the Nauru Basin igneous complex was emplaced in a relatively short period. This is a considerable outpouring of lavas because the volume of the Nauru Basin complex is believed to be at least 2×10^5 km^3 [20,22]. Moreover, the age of the Nauru Basin tholeiite is not distinct from the 114.6 ± 3.2 Ma age of the East Mariana Basin tholeiites [14] and, because of the very similar petrology and tectonic setting of the Nauru and East Mariana Basin tholeiites (see below), it is possible that the volcanism in the two basins (~ 10^6 km^2 for the two basins) was as immense as the volcanism that built the Ontong Java Plateau (~ 5×10^7 km^3) 122 m.y. ago [10].

4. Petrogenesis

The major element variation of the East Mariana Basin tholeiites can be attributed to shallow level crystal fractionation [5]. In other words, the more differentiated compositions can be produced by the removal of variable amounts of

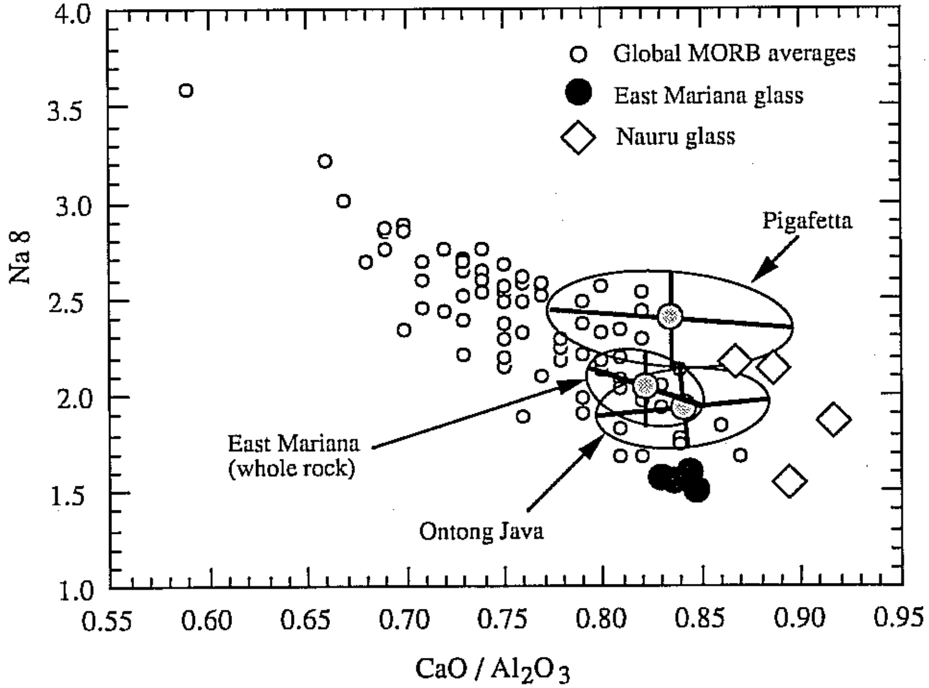

Fig. 5. Na8 against CaO/Al_2O_3 plot for the East Mariana Basin tholeiites. The spheroids represent average ± standard deviation values.

olivine, plagioclase and pyroxene from the primitive composition. The fractional crystallization relationship among East Mariana Basin tholeiites is also shown by their trace element data. The subhorizontal array of data points in the La/Yb against La diagram (Fig. 4) suggests fractional crystallization control, with the slope of the array depending upon the bulk partition coefficient of La relative to Yb [e.g., 23]. Disregarding the small seawater alteration effect on the $^{87}Sr/^{86}Sr$, the Sr, Nd and Pb isotopic ratios of the tholeiites are almost identical within errors (Table 1) and this isotopic signature is entirely consistent with the crystal fractionation history of the East Mariana Basin tholeiites.

Fig. 5 shows that the East Mariana Basin tholeiites have high CaO/Al_2O_3 and low Na8, suggesting that these rocks were produced by fairly high degrees of melting [24]. East Mariana Basin tholeiites plot on the high partial melt side of the global MORB array and are comparable only to tholeiites from a few places such as the Reykjanes Ridge, Nauru Basin and Ontong Java Plateau [10,24]. Fig. 5 also suggests that the East Mariana Basin tholeiites were erupted at ~ 2500 m water depth, using the Na8 versus depth calibration curve of Klein and Langmuir [24]. The accuracy of this depth estimate is unknown because, although the calibration curve was used to estimate the paleodepth in the Atlantic and Indian Ocean with good results [25], it has never been tested in the Pacific. The results of our attempt to use this technique for the oldest oceanic crust [12] are ambiguous, mainly due to the fact that the actual Na8 versus depth correlation for Pacific MORB is generally poor [24,26].

5. Comparison with other western Pacific tholeiites

Tholeiitic basalts were drilled in the Nauru Basin [11,18,20, 27], on the Ontong Java Plateau [10,13,28] and in the Pigafetta Basin [1,12,29] (Fig. 1). The Pigafetta Basin tholeiites were drilled at the igneous basement in ODP Site 801 (18°39′N; 156°22′W), underneath ~ 60 m of alkalic basalts and ~ 10 m of a silicified hydrothermal deposit. These tholeiites represent the oldest (~ 167 Ma) N-MORB in the world sampled in-situ. Except for the topmost ~ 5 m directly underlying the hydrothermal deposit, the Pigafetta Basin tholeiites are only slightly to moderately altered (2–10%), similar to normal oceanic crust 3–10 Ma [6,7]. Compositional variation observed in the lavas is moderate and is due to shallow level crystal fractionation. More important, the Sr, Nd and Pb isotopic ratios of these tholeiites fall almost entirely within the field of Pacific N-MORB (Fig. 3).

Compared to East Mariana Basin tholeiites, Pigafetta Basin tholeiites are more depleted in highly incompatible elements and, hence, have more convex-upward REE patterns (Fig. 2b) and have almost flat trace element abundance patterns relative to N-MORB (Fig. 2c). East Mariana Basin tholeiites have higher $^{87}Sr/^{86}Sr$ and $^{208}Pb/^{204}Pb$, for given $^{206}Pb/^{204}Pb$, than the Pigafetta Basin tholeiites (Fig. 3).

A total of ~ 640 m of tholeiitic basalt and microdolerite was drilled at DSDP Site 462 in the Nauru Basin (Fig. 1) during DSDP Legs 61 and 89. In general, Nauru Basin tholeiites seem to display a wider compositional range than East Mariana Basin tholeiites; the Nauru Basin tholeiites can be subgrouped into 3 lithologic groups, based on the relative degree of melting of a similar source in the mantle [11,27]. However, this difference is most probably due to sampling bias: Nauru Basin analyses represent > 600 m of the tholeiite igneous complex penetrated at Site 462, whereas East Mariana Basin analyses come from only ~ 51 m of tholeiite pillow lavas penetrated at Site 802. East Mariana Basin tholeiites also have slightly lower $^{206}Pb/^{204}Pb$ than Nauru Basin tholeiites, although their Pb isotopic data almost overlap (Fig. 3b). Nevertheless, these differences are minor when compared to their overall similarity.

The Nauru Basin tholeiite glass analyses [30] are richer in MgO than East Mariana Basin tholeiites, but this is also true for the Nauru Basin bulk rock data [20]. Both tholeiite suites were generated by high degrees of melting in the mantle (Fig. 5), similar to those MORB generated at ocean ridges near hotspots. The REE pattern of the East Mariana Basin tholeiite suite plots exactly in the middle of the range of the Nauru Basin basalt patterns but, more importantly, they share the same characteristic features, such as a convex-upward configuration and negative Eu anomaly (Fig. 2a). Their incompatible trace element concentration pattern is transitional between those of N-MORB and E-MORB (Fig. 2c). The relatively high ^{87}Sr/^{87}Sr for a given ^{143}Nd/^{144}Nd is a feature of both the East Mariana and Nauru Basin tholeiites (Fig. 3a). Most important, these geochemical and isotopic similarities are even more striking because their crystallization ages are very close (Table 2).

Basement tholeiitic basalts were recovered at three widely separated drill sites on the Ontong Java Plateau (DSDP Site 289 and ODP Sites 803 and 807) and from the island of Malaita on the southern margin of the plateau (Fig. 1). Based on ^{40}Ar/^{39}Ar ages, a major plateau-building effusion of these tholeiites occurred ~ 122 Ma but plateau volcanism did not cease until ~ 90 Ma [10]. The Ontong Java Plateau tholeiites have a moderate range in chemical and isotopic compositions and were presumably produced by very high extents of partial melting (Fig. 5, [13]). Moreover, they have a variable chondrite-normalized REE concentration, pattern ranging from slightly depleted to slightly enriched (Fig. 2b). By and large, their combined trace element and Sr, Nd and Pb isotope compositions strongly suggest a hotspot-like source for the Ontong Java Plateau tholeiites as well as for the less sampled and less studied Manihiki Plateau tholeiites [10,13].

Interestingly, the Sr, Nd and Pb isotopic compositions of both the East Mariana and Nauru Basin tholeiites plot within the large fields for the Ontong Java and Manihiki Plateau tholeiites (Fig. 3). However, Ontong Java Plateau tholeiites, on average, are more enriched in incompatible trace elements than East Mariana Basin (and Nauru Basin) tholeiites (Fig. 2c). Moreover, the Ontong Java Plateau tholeiites form large shield volcanoes, whereas the East Mariana and Nauru Basin tholeiites were extruded through non-edifice building volcanic fissures [1,20,22,28]. Finally, the bulk of the Ontong Java Plateau volcanic activity is ~ 7 m.y. and ~ 11 m.y. older than the East Mariana and Nauru Basin eruptions, respectively. Thus, although the tholeiites from the three areas share some similarities in their mantle source isotopic signatures, their overall major and trace element compositions, the modes of generation of their magmas in the mantle, the styles of their emplacement and the chronology of volcanic events that generated them are different.

6. Discussion

Over the last two decades, several sites in the western Pacific that were predicted to be of Jurassic age, based on magnetic lineation patterns, have been drilled to sample the basaltic crust. Because of technical difficulties in deep drilling in the 1960s to mid 1980s, only at a few of these sites did drilling actually penetrate down into igneous rocks. Furthermore, all but one of these igneous rocks turned out to be Cretaceous in age; ODP Site 802 in the East Mariana Basin is one of these Cretaceous sites [1]. What is interesting about Site 802 is that the tholeiites were intersected at a depth that was predicted, based on multichannel seismic data, to be igneous basement. The same kind of data, which were not available to guide the earlier DSDP Jurassic target sites, were used to delineate and drill successfully the Jurassic basement at Site 801 in the Pigafetta Basin just prior to drilling Site 802 during Leg 129 [1]. Moreover, the East Mariana Basin tholeiites are clearly extrusive lavas, being pillows and massive flows, as opposed to the intrusive sills that were present or interpreted as being present in the other Jurassic sites (e.g., ODP Site 800 in the northern Pigafetta Basin and DSDP Site 462 in the Nauru Basin). Site 802 is also in the middle of the East Mariana Basin, away from any known large seamount or seamount chain; other Jurassic target sites (e.g., DSDP Site 585 in the eastern part of the Mariana Basin, DSDP Site 166 in the western side of the Central Basin) turned out to be too close to prominent volcanic features, as indicated by the volcaniclastic sediments and igneous rocks recovered in the sites. Last, and most importantly, the petrology of the East Mariana Basin tholeiites is more similar to MORB erupted near hotspots than to any other type of oceanic basalts, and the Sr, Nd and Pb isotope compositions of these tholeiites are similar to some MORB from the Indian Ocean.

As presented above, the petrologic and age similarity between East Mariana and Nauru Basin tholeiites is clear. Thus, the history and evolution of the East Mariana Basin and the Nauru Basin tholeiites are essentially the same. Based on previously available data, there are two explanations proposed for the origin of the Nauru Basin tholeiites that invoke either an intraplate or ocean ridge setting. The following is a brief description of these proposals and a concise evaluation of their applicability for the origin of the East Mariana Basin tholeiites.

6.1. *The intraplate origin*

This proposal was made directly after the discovery of the Cretaceous igneous complex in the central Nauru Basin. The model suggests that the voluminous tholeiites, which are anomalously shallow for a Jurassic age igneous basement, cover the whole Jurassic basement of the basin and were emplaced through numerous small fissures in the pre-existing Jurassic crust [20,31]. Explicit in this proposal is that the fissures did not cause substantial reheating of the oceanic crust to disturb the original well-preserved Jurassic magnetic lineations, that these lineations were all aligned parallel to the magnetic stripes so as not to cause displacement of the magnetic lineations, and that they were most probably confined to the Nauru Basin. Moreover, this Cretaceous cover must have cooled very rapidly and acted as a uniformly magnetized slab so that it did not annihilate the underlying Jurassic magnetic signal [31]. Interestingly, this proposal was made during DSDP Leg 61, with the assumption that the Jurassic sediments and igneous basement were only a few meters beneath the bottom of the hole at Site 462. The site was reoccupied and deepened by ~ 140 m during DSDP Leg 89, but the bottom contact between the Cretaceous basalts and the Jurassic sediments still was not reached [20]. Despite the unconfirmed stratigraphy, however, the intraplate basalt proposal for the origin of the Nauru Basin igneous complex has gained wide acceptance because more recent paleomagnetic studies have confirmed the presence of Jurassic magnetic anomalies in the Nauru Basin [32,33].

A variation of this proposal claims that the large-volume flows and sills in the Nauru Basin did not intrude the Jurassic crust but rather originated from the adjacent Ontong Java Plateau [E. Winterer, pers. commun., 1991] at ~ 111 Ma. Still another variation of the proposal, but intended more for the presumably thin East Mariana Basin flows and not for the thick Nauru Basin igneous complex, claims that the basalts were erupted through fissures generated by the downbuckling and extension of the Jurassic crust due to the load of the Ontong Java Plateau [34]. This scenario is essentially a larger version of the mechanism proposed for the origin of Hawaiian arch lavas generated on either side of the Hawaiian Ridge [35].

6.2. *The ocean ridge origin*

This proposal is based mainly on the MORB-like petrology and isotopic composition of the Nauru Basin tholeiites and on the premise that these compositional characteristics of a large-volume igneous complex can be sustained only through continuous eruption along large rifts or an ocean ridge system [11,27]. It is also partly based on the premise that because the Cretaceous Pacific ocean ridges were spreading fast (~ 10 km/yr half-rate; [2]) in a large ocean, a simple extrapolation of symmetric accretion to produce the whole western Pacific crust from Jurassic to the present may be too simplistic, as shown by new magnetic lineation data near the EPR [e.g., 35,36]. This notion of asymmetric spreading near mantle plumes is based on observations along the EPR near the Easter hotspot [38], along the Galapagos Spreading Center near the Galapagos hotspot [39], and along the MAR at the Iceland hotspot [40]. It is important to note that, since at least the early Cretaceous, the south-central Pacific region may have been volcanically active; perhaps, because of mantle convection [41,42] such that large plateaus (e.g., Ontong Java and Manihiki Plateaus) and chains of large seamounts and guyots (e.g., Mid-Pacific Mountains and Magellan Seamounts) were produced in this general area during this period [11,12,43,44]. In fact, Tarduno et al. [45] have suggested that the formation of the Ontong Java Plateau by an Aptian mantle plume alone could have initiated rifting of the Jurassic seafloor proximal to the plateau. In summary, the ocean ridge proposal claims that large rifts or an ocean spreading center opened or propagated into the northern part of the Nauru Basin during the Cretaceous and formed the Nauru Basin igneous complex.

6.3. Which proposal is more applicable to the East Mariana Basin tholeiites?

As mentioned earlier, any model that could explain the origin of the Nauru Basin tholeiites would most likely also apply to the origin of the East Mariana Basin tholeiites. The major problem with the intraplate basalt proposal is that the bulk major and trace element compositions of both the Nauru and East Mariana Basin tholeiites are not representative of an intraplate eruptive setting. Proposals that the Nauru Basin tholeiites are a new kind of intraplate oceanic basalt [e.g., 20,22] simply make the scenario more complex. Another problem is the emplacement of these large volume MORB-like tholeiites. Were the Nauru Basin tholeiites emplaced through numerous small fissures throughout the basin, as proposed by the intraplate hypothesis? New seismic reflection data show that the top of the Jurassic oceanic crust is not present in the northern part of the basin, but unequivocally exists in the southern part [46]. This tectonic setting simply cannot be reconciled with the intraplate proposal. Were the East Mariana Basin tholeiites emplaced through numerous fissures? Maybe so, as new multichannel seismic studies claim that the tholeiites are only ~400 m thick with no obvious morphotectonic sources other than widely separated seamounts [47]. However, the same studies [47] show that the Cretaceous MORB-like tholeiites cover not only the East Mariana Basin but also the southern Pigafetta Basin, indicating that a very large portion of the western Pacific Jurassic crust was highly porous to the voluminous, high-degree partial (i.e., high temperature) melts coming from the mantle during the Cretaceous. This extensive magmatic infiltration did not disturb the magnetic anomaly pattern of the original basement.

That the Nauru Basin tholeiites, and, hence, the East Mariana Basin tholeiites, came directly from the Ontong Java Plateau may also not be realistic. This is because almost all the sills and lava flows are glassy and < 1 m thick, suggesting that they must have come from a nearby source [1,11,20]. The biggest problem, of course,is that the OIB-like chemistry of the Ontong Java Plateau lavas is more variable and quite distinct from the MORB-like Nauru and East Mariana Basin tholeiites, although, as mentioned earlier, they do overlap, especially in their isotopic compositions. Moreover, although the last recorded volcanism on Ontong Java Plateau occurred ~90 Ma, the last major phase of the voluminous, plateau-building volcanism occurred ~122 Ma [10]. Were there large-volume MORB-like basalts erupted along the flanks of the Ontong Java Plateau ~11 m.y. after the plateau was built? Why was this volcanic activity not recorded in any of the drill sites on the Ontong Java Plateau? Similarly, the theory of the origin of the East Mariana Basin tholeiites from small fissures induced by the load of the Ontong Java Plateau on the Jurassic crust suffers from the inconsistency of the lava composition to this particular type of setting [34]. The Hawaiian arch lavas, in the small-scale analogue, are alkalic in composition and are akin to the Hawaiian basalt composition [35].

Our favored explanation for the origin of the East Mariana Basin MORB-like tholeiites is that these, and the Nauru Basin tholeiites, were formed along a Cretaceous spreading center. This proposal conflicts with the suggestion, based on magnetic lineation data, that these basins are underlain by Jurassic basement but the repeated occurrence of Cretaceous basalts in this area provides no support for the older age inferred from the magnetic data in the whole western Pacific. The ocean ridge proposal claims that the rift(s) or spreading center(s) is (are) restricted to the northern part of the basin [11] and this is consistent with the new seismic reflection data [46]. This proposal also implies that the rifts or spreading centers continue to the east and west sides of the Nauru Basin, but these are displaced by north–south trending transform faults that bound the east and west sides of the basin. The East Mariana Basin tholeiites most probably accreted along the western extension of the spreading center, whereas the, as yet poorly analyzed, Cretaceous MORB-like tholeiites recovered from the Central Basin during DSDP Leg 17 [48] formed along the eastern counterpart. Petrologic analyses of the Central Basin tholeiites are currently in progress to assess their petrogenetic connection with the East Mariana and Nauru Basin tholeiites.

The major and trace element data for both the East Mariana and Nauru Basin tholeiites are consistent with a shallow, widespread, and high degree partial melting of suboceanic mantle typical of an ocean ridge setting. However, the isotopic similarity with the Ontong Java and Manihiki Plateau basalts, which are presumed to be mantle plume generated, suggests that the mantle source of the East Mariana and Nauru Basin lavas contained material coming from the mantle plume(s) responsible for the formation of these large oceanic plateaus. Therefore, we suggest that the ocean ridge volcanism that produced the East Mariana and Nauru Basin tholeiites is a direct result of the Ontong Java mantle plume. The petrologic and isotopic characteristics of the East Mariana and Nauru Basin tholeiites are, indeed, fairly common in modern plume-related MORB although these MORB are less voluminous and more limited in areal extent compared to the East Mariana and Nauru Basin basalts. It is important to note, however, that the oceanic hotspot responsible for the formation of the Ontong Java Plateau is the world's largest and its activity coincided with the widespread volcanic event in the Pacific during the Cretaceous [e.g., 45,48].

7. Summary and conclusions

Drilling in the East Mariana Basin during ODP Leg 129 failed to sample the targeted Jurassic oceanic crust that was predicted to be present, based on seafloor magnetic lineation patterns. Instead, Cretaceous lavas that seem to be ubiquitous in the western Pacific were recovered. However, the East Mariana Basin basalts are unique in that these are extrusive lavas and MORB-like in geochemical and isotopic composition. Compositionally and temporally, the tholeiites are very similar to Nauru Basin tholeiites, which were also targeted as Jurassic oceanic crust during DSDP Legs 61 and 89, based on interpretation of magnetic lineation patterns. The two Cretaceous MORB-like tholeiite suites must, therefore, have a very similar, if not common, origin.

The two existing hypotheses for the origin of the Nauru Basin tholeiites specify either intraplate or ocean ridge settings. Many of the initial assumptions of the intraplate proposal are either inconsistent with new data available and/or have to be carefully tested to explain the origin of the East Mariana Basin tholeiites. On the other hand, the presence of the East Mariana Basin tholeiites is simply an extension of the ocean ridge proposal for the origin of the Nauru Basin MORB-like tholeiites. Although this explanation is still speculative, it is based on actual analyses of samples recovered from the two basins and on more recent data showing that fast-spreading ridges tend to deviate from symmetric spreading, especially when affected by off-ridge volcanism. Therefore, we favor an ocean ridge origin for the East Mariana and Nauru Basin tholeiites and suggest that these basalts represent oceanic crust generated along a Cretaceous spreading center. This spreading center was a consequence of the arrival in the upper mantle of a plume that produced the huge Ontong Java and Manihiki Plateaus. The shallow, high-degree mantle melting condition under the Cretaceous spreading center, adjacent to a plume, shaped the MORB-like major and trace element characteristics of the East Mariana and Nauru Basin tholeiites but the plume-dominated mantle source dictated the isotopic composition of these lavas.

Acknowledgments

We thank J. Mahoney for providing the Nauru Basin tholeiite glasses and R. Duncan, R. Larson and H. Staudigel for their careful and scholarly reviews. This work is partly supported by grants Texas A&M PO20511 and NSF-OCE91-96025 to PC.

References

[1] Y. Lancelot, R. Larson, et al., Proc. ODP, Init. Rep. 129, 1990.

[2] R.L. Larson, Late Jurassic and Early Cretaceous evolution of the western Pacific Ocean, J. Geomagnet. Geoelec. 28, 219–236, 1976.

[3] Basaltic Volcanism Study Project, Basaltic Volcanism on the Terrestrial Planets, 286 pp., Pergamon, New York, 1981.

[4] M.S. Pringle, Radiometric ages of basaltic basement recovered at Sites 800, 801, and 802, ODP Leg 129, western Pacific Ocean, Proc. ODP, Sci. Results 129, 389–404, 1992.

[5] P.A. Floyd, J.A. Winchester and P.R. Castillo, Geochemistry and petrography of Cretaceous sills and lava flows, Site 800 and 802, Proc. ODP, Sci. Results 129, 345–359, 1992.

[6] J.C. Alt, C. France-Lanord, P.A. Floyd, P.R. Castillo and A. Galy, Low-temperature hydrothermal alteration of Jurassic ocean crust, ODP Site 801, Proc. ODP, Sci. Results 129, 415–430, 1992.

[7] W.H. Busch, P.R. Castillo, P.A. Floyd and G. Cameron, Effects of alteration on physical properties of basalts from the Pigafetta and East Mariana Basins, Proc. ODP, Sci. Results 129, 485–500, 1992.

[8] W.G. Melson, T.L. Vallier, T.L. Wright, G.R. Byerly and J.A. Nelen, Chemical diversity of abyssal volcanic glass erupted along Pacific, Atlantic, and Indian Ocean seafloor spreading centers, Geophys. Monogr. 19, 351–368, 1976.

[9] J.W. Jacobs, R.L. Korotev, D.P. Blanchard, et al., A well-tested procedure for instrumental neutron activation analysis of silicate rocks and minerals, J. Radioanal. Chem. 40, 93–114, 1977.

[10] J.J. Mahoney, M. Storey, R.A. Duncan, K.J. Spencer and M.S. Pringle, Geochemistry and geochronology of the Ontong Java Plateau, in: Mesozoic Pacific, M. Pringle, W. Sager, W. Sliter and S. Stein, eds., AGU Monogr. 77, 233–261, 1993.

[11] P.R. Castillo, R.W. Carlson and R. Batiza, Origin of Nauru Basin igneous complex: Sr, Nd and Pb isotope and REE constraints, Earth Planet. Sci. Lett. 103, 200–213, 1991.

[12] P.R. Castillo, P.A. Floyd and C. France-Lanord, Isotope geochemistry of ODP Leg 129 basalts: implications for the origin of the widespread Cretaceous volcanic event in the Pacific, Proc. ODP, Sci. Results 129, 405–414, 1992.

[13] J.J. Mahoney, An isotopic survey of Pacific Oceanic Plateaus: implications for their nature and origin, in: Seamounts, Islands, and Atolls, B. Keating, P. Fryer, R. Batiza, and G. Boehlert, (eds.), Am. Geophys. Union Monogr. 43, 207–220, 1987.

[14] M.S. Pringle, Geochronology and petrology of the Musician Seamounts, and the search for hotspot volcanism in the Cretaceous Pacific, Ph.D. Thesis, Univ. of Hawaii, Manoa, Honolulu, 1992.

[15] H.S. Staudigel and W.B. Bryan, Contrasted glass–whole rock compositions and phenocryst re-distribution, IPOD Sites 417 and 418, Contrib. Mineral. Petrol. 78, 255–262, 1981.

[16] Y. Takigami, S. Amari, M. Ozima and R. Moberly, ^{40}Ar/^{39}Ar geochronological studies of basalts from Hole 462A, Nauru Basin, Deep Sea Drilling Project Leg 89, Init. Rep. DSDP 89, 519–521, 1986.

[17] A. Schaaf, Radiolaria from Deep Sea Drilling Project Leg 89, Init. Rep. DSDP 89, 321–326, 1986.

[18] I. Primoli-Silva, A new biostratigraphic interpretation of the sedimentary record recovered at Site 462, Leg 61, Nauru Basin, western equatorial Pacific, Init. Rep. DSDP 89, 311–320, 1986.

[19] M. Ozima, K. Saito, and Y. Takigami, ^{40}Ar/^{39}Ar geochronological studies on rocks drilled at holes 462 and 462A, Deep Sea Drilling Project Leg 61, Init. Rep. DSDP 61, 701–703, 1981.

[20] R. Larson, S.O. Schlanger, et al., Init. Rep. DSDP 61, 1981.

[21] S.R. Hart and H. Staudigel, Ocean crust vein mineral deposition: Rb/Sr ages, U–Th–Pb geochemistry, and duration of circulation of DSDP Sites 261, 462 and 516, Geochim. Cosmochim. Acta 50, 2151–2761, 1986.

[22] R. Moberly, S.O. Schlanger, et al., Init. Rep. DSDP 89, 1986.

[23] J.F. Minster and C.-J. Allègre, Systematic use of trace elements in igneous processes. Part III: Inverse problem of batch partial melting in volcanic suites, Contrib. Mineral. Petrol. 68, 37–62, 1978.

[24] E.M. Klein and C.H. Langmuir, Global correlations of ocean ridge basalt chemistry with axial depth and crustal thickness, J. Geophys. Res. 92, 8089–8115, 1987.

[25] M.J. Keen, E.M. Klein and W.G. Melson, Ocean ridge basalt compositions correlated with paleobathymetry, Nature 345, 423–426, 1990.

[26] J. Brodholdt and R. Batiza, Global systematics of unaveraged mid–ocean ridge basalt compositions: comment on "Global correlations of ocean ridge basalt chemistry with axial depth and crustal thickness" by E.M. Klein and C.H. Langmuir, J. Geophys. Res. 94, 4231–4239, 1989.

[27] P.R. Castillo, R. Batiza and R. Stern, Petrology and geochemistry of Nauru Basin igneous complex: large-volume, off-ridge eruptions of MORB-like basalt during the Cretaceous, Init. Rep. DSDP 89, 555–576, 1986.

[28] L.W. Kroenke, W.H. Berger, T.R. Janecek, Proc. ODP, Init. Rep. 130, 1991.

[29] P.A. Floyd, P.R. Castillo and M. Pringle, Tholeiitic and alkalic basalts of the oldest Pacific Ocean crust, Terra Nova 3, 257–265, 1990.

[30] H. Tokuyama and R. Batiza, Chemical composition of igneous rocks and origin of the sill and pillow basalt complex of Nauru Basin, southwest Pacific, Init. Rep. DSDP 61, 673–687, 1981.

[31] R.L. Larson and S.O. Schlanger, Cretaceous volcanism and Jurassic magnetic anomalies in the Nauru Basin, western Pacific Ocean, Geology 9, 480–484, 1981.

[32] M. Nakanishi, K. Tamaki and K. Kobayashi, A new Mesozoic isochron chart of the northwest Pacific Ocean: paleomagnetic and tectonic implications, Geophys. Res. Lett. 19, 693–696, 1992.

[33] M. Nakanishi, K. Tamaki and K. Kobayashi, Magnetic anomaly lineations from Late Jurassic to Early Cretaceous in the west-central Pacific Ocean, Geophys. J. Int. 109, 701–719, 1992.

[34] P.R. Castillo and M. Pringle, Cretaceous volcanism in the western Pacific, EOS Trans Am. Geophys. Union 72, 300, 1991.

[35] D.A. Clague, R.T. Holcomb, J.M. Sinton, R.S. Detrick and M.E. Torresan, Pliocene and Pleistocene alkalic flood basalts on the seafloor north of the Hawaiian islands, Earth Planet. Sci. Lett. 98, 175–191, 1990.

[36] G.F. Sharman and J. Mammerickx, Eastern boundary of the Manihiki Plateau; a propagating rift site, EOS Trans Am. Geophys. Union 71, 1668, 1990.

[37] J. Mammerickx, The Foundations Seamounts: tectonic setting of a newly discovered seamount chain in the South Pacific, Earth Planet. Sci. Lett. 113, 293–306, 1992.

[38] R.N. Hey, D.F. Naar, M.C. Kleinrock, W.J. Phipps Morgan, E. Morales and J.-G. Schilling, Microplate tectonics along a superfast seafloor spreading system near Easter Island, Nature 317, 320–325, 1985.

[39] R.N. Hey, Tectonic evolution of the Cocos–Nazca spreading center, Geol. Soc. Am. Bull. 88, 1404–1420, 1977.

[40] P.R. Vogt, Seafloor topography, sediments, and paleoenvironments, in: The Nordic seas, B.G. Hurdle, ed., pp. 237–410, Springer, New York, 1986.

[41] P.G. Silver, R.W. Carlson and P. Orlson, Deep slabs, geochemical heterogeneity and the large-scale structure of mantle convection: an investigation of an enduring paradox, Annu. Rev. Earth Planet. Sci. 16, 477–541, 1988.

[42] P. Castillo, The Dupal anomaly as a trace of the upwelling lower mantle, Nature 336, 667–670, 1988.

[43] W.H.F. Smith, H. Staudigel, A.B. Watts, and M.S. Pringle, The Magellan Seamounts: Early Cretaceous record of the south Pacific isotopic and thermal anomaly, J. Geophys. Res. 94, 10501–10523, 1989.

[44] H. Staudigel, K.-H. Park, M. Pringle, J.L. Rubenstone, W.H.F. Smith and A. Zindler, The longevity of the South Pacific isotope and thermal anomaly, Earth Planet. Sci. Lett. 102, 24–44, 1991.

[45] J.A. Tarduno, W.V. Sliter, L. Kroenke, M. Leckie, H. Mayer, J.J. Mahoney, R. Musgrave, M. Storey and E.L. Winterer, Rapid formation of Ontong Java Plateau by Aptian mantle plume volcanism, Science 254, 399–403, 1991.

[46] T.H. Shipley, L.J. Abrams, Y. Lancelot and R.L. Larson, Late Jurassic–Early Cretaceous oceanic crust and Early Cretaceous volcanic sequences of the Nauru Basin, western Pacific, in: M. Pringle, W. Sager, W. Slitter, and S. Stein, eds., AGU Monograph 77, 103–119, 1993.

[47] L.J. Abrams, R.L. Larson, T.H. Shipley, and Y. Lancelot, Cretaceous volcanic sequences and Jurassic oceanic crust in the East mariana and Pigafetta Basins of the western Pacific, in: Mesozoic Pacific, M. Pringle, W. Sager, W. Sliter and S. Stein, eds., AGU Monogr. 77, 77–101, 1993.

[48] E.L. Winterer, Ewing, J.I., et al., Init. Rep. DSDP 17, 1973.

[49] S. Shafik, Nannofossil biostratigraphy of the southwest Pacific, DSDP Leg 30, Init. Rep. DSDP 30, 549–598, 1975.